NGCPV: A NEW GENERATION OF CONCENTRATOR PHOTOVOLTAIC CELLS, MODULES AND SYSTEMS

A.B. Cristóbal[1], A. Martí[1], G. Sala[1], A. Bett[2], N. J. Ekins-Daukes[3], F. Roca[4], I. Luque-Heredia[5], W. Warmuth[6], J. Merten[7], Y. Okada[8], Y. Hishikawa[9], T. Takamoto[10], K. Araki[11], A. Fukuyama[12], N. Kuze[13], T. Kita[14], A. Kotagiri[15], M. Yamaguchi[8, 16], A. Luque[1]

[1]Instituto de Energía Solar - Universidad Politécnica de Madrid (IES-UPM). [2]Fraunhofer ISE. [3]Imperial College of Science, Technology and Medicine (ICSTM). [4]Italian National Agency for new Technologies, energy and sustainable economic development (ENEA). [5]BSQ Solar S.L. [6]PSE AG, *Germany*. [7]Institut National de l'Energie Solaire (INES/CEA). [8]The University of Tokyo, *Japan*. [9]National Institute of Advanced Industrial Science and Technology (AIST), *Japan*. [10]Sharp Co., Japan.[11]Daido Steel Co., Ltd, *Japan*. [12] University of Miyazaki, *Japan*. [13]Asahei- Kasei, *Japan*. [14]The University of Kobe, *Japan*. [15]Takano Co., Ltd, *Japan*. [16]Toyota Technological Institute, *Japan*.

[1]Avenida Complutense 32, 20840 Madrid (Spain).[2] Heidenhofstrasse 2, 79110 Freiburg (Germany). [3]Prince consort Road, London SW7 2AZ (United Kingdom). [4] P. Le E. Fermi, 1 (Localita Granatello) 80055 Portici, NA (Italy). [5] Calle del Vivero 5, 28040 Madrid (Spain). [6] Emmy-Noether-Strasse 2, 79110 Freiburg (Germany). [7] Savoie Tecnolac BP332 50, avenue du Lac Leman, 73377 Le Bourget du lac Cedex (France). [8] 4-6-1 Komaba, Meguro, Tokyo 153-8904 (Japan). [9]1-1-1 Umezono, Tsukuba, Ibaraki 305-8565 (Japan). [10] 492 Minosho, Yamato-Kooriyama, Nara 639-1186 (Japan).[11] 9 Takiharu, Minami, Nagoya 457-8712 (Japan).[12] 1-1 Gakuen Konohanadai-nishi, Miyazaki 889-2192 (Japan). [13] 2-1 Samejima, Fiji, Shizuoka 416-8501 (Japan). [14] 1-1 Rokkodai , Nada, Kobe 657-8051 (Japan). [15] 137 Miyata, Kami-Ina, Nagano 399-4301 (Japan). [168] 2-12-1 Hisakata, Tempaku, Nagoya 468-8511 (Japan).

ABSTRACT: This work introduces the lines of research that the NGCPV project is pursuing and some of the first results obtained. Sponsored by the European Commission under the 7th Framework Program and NEDO (Japan) within the first collaborative call launched by both Bodies in the field of energy, NGCPV project aims at approaching the cost of the photovoltaic kWh to competitive prices in the framework of high concentration photovoltaics (CPV) by exploring the development and assessment of concentrator photovoltaic solar cells and modules, novel materials and new solar cell structures as well as methods and procedures to standardize measurement technology for concentrator photovoltaic cells and modules. More specific objectives we are facing are: (1) to manufacture a cell prototype with an efficiency of at least 45% and to undertake an experimental activity, (2) to manufacture a 35% module prototype and elaborate the roadmap towards the achievement of 40%, (3) to develop reliable characterization techniques for III-V materials and quantum structures, (4) to achieve and agreement within 5% in the characterization of CPV cells and modules in a round robin scheme, and (5) to evaluate the potential of new materials, devices technologies and quantum nanostructures to improve the efficiency of solar cells for CPV.
Keywords: III-V Semiconductors, Concentrators, Reliability, Quantum Well, Quantum Dots, Characterisation.

1 DEADLINES AND DELIVERY

1.1 Policy scenario

In March 2007, the EU's leaders endorsed an integrated approach to climate and energy policies that aim at fighting against climate change and increase the EU's energy security while strengthening its competitiveness. They committed Europe to transform itself into a highly energy-efficient, low carbon economy. To quickly start this process, the EU Heads of State and Government set a series of demanding climate and energy targets to be met by 2020, known as the "20-20-20" targets. These are:

- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels.
- 20% of EU energy consumption to come from renewable resources.
- A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

Concurrently, the Japanese Prime Minister Fukuda presented his vision to the press on the 9th of June of 2008 on "Cool Earth in 2050" where the contribution of PV to this vision was taken into account in several PV programs and taking into account several temporal scenarios. The present Japanese Government supports this vision. Specific objectives of "Cool Earth in 2050" are:

- A reduction in Japan CO_2 emission of at least 25% below 1990 levels until 2020.
- Cumulative PV capacity with 14GW and 53GW until FY2020 and FY2030, respectively.

RTD is one of the key factors for achieving this goal. The Directorate-General Research, with the support of the several services of the EC including the Joint Research Centre and in particular of the Institute of Energy together with the New Energy and Industrial Technology Development Organization (NEDO) of Japan, devised a cooperative strategy that was materialized by the issue, on July 20th, 2010, of the call FP7-ENERGY-2011-JAPAN: Ultra-high Efficiency Concentration Photovoltaics (CPV) Cells, Modules and Systems /EU-Japan Coordinated Call.

NGCPV Project responds to this Call and, with its impact, is expected to contribute to the achievement of both the "20-20-20" and "Cool Earth in 2050" targets. The project started on June 2011 and will end on November 2014.

1.2 CPV Research & Development Scenario

Concentrator Photovoltaics Technology has reached commercialization. Approximately 21 MW of Concentrator Photovoltaics (CPV) systems were installed in 2011[1] and the market is expected to reach a GW level in the next 5 years. With multiple commercial scale power plants connected to the grid in 2011, CPV technology is now ready for taking-off. Although considerable progress has already been made in the development and manufacturing of CPV, there are still huge possibilities to further increase their efficiency while reducing their cost.

NGCPV research is focused on the development and demonstration of new concepts for devices and processes for very high efficiency photovoltaic and on new characterization techniques suitable for such solar cells.

2 NEW MATERIALS AND DEVICE CHARACTERIZATION

NGCPV devotes part of its effort to the development of reliable characterization techniques for III-V materials and quantum nanostructures.

Along this project, several novel cells for their use under concentrated light are going to be manufactured. Current activity responds to the need of characterizing them at material and device level. This includes more or less conventional techniques but also advanced techniques. Among the "conventional" ones we count, for example, transmission electron microscopy (TEM), photoluminescence (PL), photoreflectance (PR), deep level transient microscopy, surface photovoltage and time resolved photoluminescence. Among the advanced techniques we could list two newly developed techniques: the three dimensional real-time reciprocal space mapping (3D-RTSM) and the piezoelectric photo-thermal (PPT) techniques. On the other hand, carrying out characterization at device level not only implies characterization of solar cell devices but ad-hoc devices made of raw solar cells materials. Actually, their specific characterization as solar devices is included in the activity described in section 5.

The framework of cooperation provided by this Project will offer an excellent opportunity to carry out also a kind of round-robin around these techniques to find out whether all the laboratories get the same kind of signatures and to extract the best of each one.

3 NOVEL DEVICE TECHNOLOGIES AND QUANTUM STRUCTURES

This action is specifically devoted to the achievement of the objective: to evaluate the potential of new materials, device technologies and quantum nanostructures to improve the efficiency of solar cells for CPV (Fig 1).

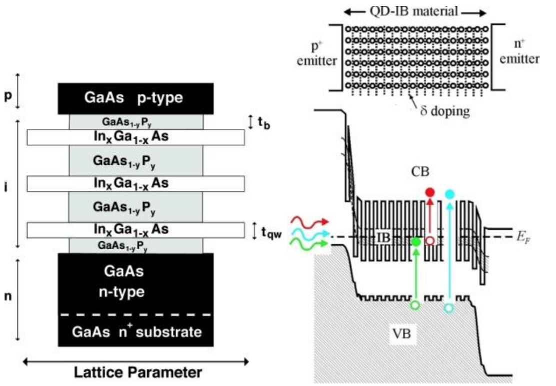

Fig 1. (Left) Schematics of a strain balance Multi-quantum wells. (Right) Scheme of a QD IBSC.

Multiple quantum wells (MQWs) are nanostructures that offer the potential for tailoring the semiconductor bandgap by controlling, once the appropriate materials have been chosen, the dimensions of the QWs. They can be used in the lattice-matched approach to tune the

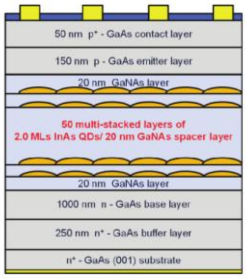

Fig 2 (a) Schematic structure of QDSC with multi-stacked layers of InAs/GaNAs straincompensated QDs.

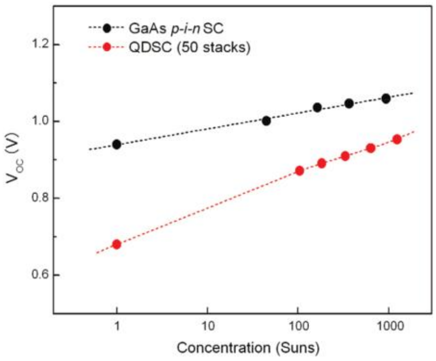

Fig 2 (b) Measured Voc as a function of concentration. A rapid initial recovery in Voc is observed up to ~100 suns for 50-layer stacked InAs/GaNAs strain-compensated QDSC.

bandgap of the cells and improve their current matching. The present design for the MQW solar cell is based on a p-i-n structure with uniform multiple quantum wells placed in a periodic stack in the intrinsic region. This structure is convenient to grow and leads to high single junction efficiency (28.3% at 535 suns), but is unlikely to be optimal. There are two key areas in which significant improvement could be made. To maximize optical absorption over the intrinsic region, the well depth and width should be varied as light propagates deeper into the device structure. In addition, to minimize parasitic recombination, it is desirable to have shallow quantum wells, or possibly even no quantum wells, residing in the centre of the intrinsic region where the n p product and hence Shockley-Read-Hall recombination will peak. These near-term improvements will greatly assist any implementation for a quantum well solar cell, either as a single junction device or as a component in a multi-junction stack.

As bandgap tailoring tool, quantum wells can also be used to achieve a 1 eV junction, suitable for making a highly efficient multijunction solar cell. It is challenging to grow an InGaAs quantum well with an absorption edge at 1eV, but this can be achieved relatively easily using dilute nitride materials, such as InGaAsN or GaAsN. Most attempts to date have attempted to grow GaAsN or InGaAsN with GaAs barriers. Here we investigate to make a strain-balanced InGaNAs/InGaAs or GaAsN/InGaAs multi-quantum well absorber where InGaAs becomes the barrier material and dilute nitride material becomes the quantum well. Several benefits arise with this structure over a conventional structure with GaAs barriers. Firstly, the use of InGaAs barriers increases the density of states over those introduced by the dilute nitride quantum well material. Secondly by using a strain-balanced structure, InGaAs/GaAsN can be grown dislocation free on a GaAs substrate leading to the highest possible material quality. Thirdly by controlling the strain of the quantum well structures, the effective masses can be optimised to give the highest possible optical absorption up to the 1eV threshold in this quantum well structure.

Quantum dots (QDs), on the other hand, offer the potential for absorbing two below bandgap energy photons and increase the photocurrent of the cell without voltage degradation accordingly to the "intermediate band (IB)" solar cell concept. Under the QD approach, the IB would arise from the energy levels of confined electrons in the conduction band. One of the key additional aspects of this approach is related to the preservation of the output voltage of the cell, which means that the open-circuit voltage of the cell is not limited by the intermediate band [2]. To progress further, the Project will study practical issues like the impact of QD doping in the performance of the cells as theoretical ones forwarded to improve our understanding of absorption of light in QDs. Recently, the characteristics of InAs/GaAsN strain-compensated QD intermediate band (IB) solar cells under concentrated light have also been studied, showing a convergence between the opencircuit voltage of the reference and the QD cell [3]. (Fig. 2)

4. DEVELOPMENT OF ADVANCED CPV CELLS

This work package is specifically devoted to the development and manufacturing of multijunction solar cell (MJSC) structures pursuing objective of manufacturing a cell prototype with an efficiency of at least 45%, and to undertake an experimental activity plan towards the achievement of 50%.

Up to now, two basic strategies have been followed to achieve high efficiencies: the lattice-matched and the metamorphic approach. In the first, growing materials with almost the same lattice constant than the substrate pursues the high efficiency. However, due to the restriction of using materials that are lattice-matched to a substrate, the band gap combinations are not optimal leading to strong differences in the subcells photocurrents. So for these cells, the key issue is to improve current matching since the materials of the subcells and hence their bandgaps are fixed due to the lattice-match to the germanium substrate. Part of this activity is being developed in collaboration with the activities described in previous section, promoting the innovative solution of the implementation of quantum nanostructures into germanium based three junction lattice-matched structures. Another strategy that is being pursed within the project consists in including InGaAsN middle cells for four multijunction junction lattice-matched structures. To improve electrical properties of the InGaAsN material a profound understanding of N-related defects is very important.

On the contrary, good current matching can be achieved through the metamorphic approach to the expense of some potential degradation in the material quality. Metamorphic materials are grown on a substrate or layer but the growing layers have a different lattice constant than the underlying substrate, offering a high flexibility in materials. Within this activity both metamorphic and inverted metamorphic are being investigated. For the first ones the initial focus has been on the development of buffer structures that are suitable to realize four junction cells, which includes an InGaAs sub cell with a band gap of 1.0 eV. While for the second ones, solar cells have been grown by MOCVD on a GaAs substrate by SHARP. GaInP top and GaAs middle cell layers which are lattice matched to the substrate are grown at first and then the lattice mismatched InGaAs bottom cell is grown at last, in inverted order. After the growth of the cell layers they are separated from the GaAs substrate, and are mounted on a Si substrate by using metal bonding. It worth highlighting that we renewed the world record efficiency under 1sun in the IMM-3J cell from previous 35.8% to 36.9% [4]. Later on, FhG-ISE has confirmed that cells manufactured by SHARP with this method have achieved 43.5% efficiency [5].

Within this activity and in order to identify where efficiency is lost and improve future devices several works of operational modelling are being carried out. These initial investigations will be the basis for model-based optimization of multi-junction solar cells towards higher efficiencies. The sets of tasks are completed by reliability tests in order to determine how stable the high efficiency devices are with time.

5 DEVELOPMENT OF CHACTERIZATION TOOLS FOR CPV CELLS, MODULES AND SYSTEMS

This activity pursues to evaluate the potential of new materials, device technologies and quantum nanostructures to improve the efficiency of solar cells for CPV; to carry out the full evaluation of a 50 kW CPV experimental plant and to achieve the peak power definition for concentration plants and rules for the forecast of their energy production.

Characterization of modern CPV cells and modules requires specific procedures in relation to their need of collimated illumination, spectral dependence of light and thermal dissipation. The combination of indoor and outdoor testing will provide the most complete information.

Outdoor cell test allows presenting the thermal effects on the cell parameters and unveil the possible problems related with the structure of the new materials. It is not a qualification test but is similar to a short exposure test. For modules, the outdoor testing , unveils the problems of new cells, new optics and their combined operation. In this context a new characterization tool has been already designed to allow the outdoor testing of single III-V cells and the outdoor testing of single III-V cells and elementary concentrator optics. This tool called OSFAM (One Size Fits All Module) and the first prototype have been designed considering inputs from NGCPV partners and has been fabricated by CEA. The second version of this tool is under construction at the moment. Within the following months characterization of solar cells and modules with this tool will take place.

On the other hand the indoor cell characterization of solar cells gives the most complete information on cell parameters because spectrum, irradiance, light distribution and cell temperature can be controlled independently. Indoor testing modules is accepted as a key element for the industrial progress of CPV business and their indoor rating values. The indoor power-rating of modules is the key figure for manufactures which should rate the module power in a repeatable and realistic way. Our laboratories are currently preparing their characterization set-ups for providing the first results [6].

The round-robin methodology is considered a very convenient procedure to standardization and modeling. In this context the Project has programmed a round robin scheme for outdoor and indoor characterization of cells and modules. We compare and evaluate the results obtained by different laboratories in order to define accurate measurements technologies for the CPV devices such as the irradiance adjustment, spectral irradiance, uniformity, divergence angle, pulse with, etc.. At the moment, several sets of cells have been already mounted for the use as reference cells for cell round robins. Each set consists of one top, one middle and one bottom component (single junction) cell and one corresponding lattice matched triple-junction cell.

Finally, the characterization of a 50 kW CPV experimental plant that has been already built by members of the Consortium will provide first hand experience to work out the power definition for concentration plants and rules for the forecast of their energy production. Two methods are envisaged, based on: a) averaged parameters (soiling, effective radiation available for spectrum sensitive cells); b) continuous modelling of the whole system according the averaged meteorology and radiation parameters. Characterization will imply the development of suitable tools as for example those needed for remote characterization. Results will be contrasted with results from a 5kW CPV system already located in Italy what will allow also learning from comparison between both.

6 DEVELOPMENT OF CPV MODULES AND SYSTEMS

Within this activity a new type of module will be investigated aiming at the achievement of the objective of manufacturing a 35% module prototype and elaborate the roadmap towards the achievement of 40%. In this Project, we have named this module as “INTREPID” HCPV module. It is important that, at the time a high efficiency module is manufactured, this can be characterized during the manufacturing process and to this end we have also stated the objective of achieving integration of characterization tools in the manufacturing process.

It is extremely difficult to obtain high performance from large size array of modules. There are a lot of reasons. The common problems are the mismatching losses inherent to optical misalignment, optics variance and tracking error. The issue of the scalability is now understood stemmed from optical alignment and a key to overcoming it is the improvement of the tolerance to the optical design.

By the combination of the non-imaging dome-shaped Fresnel lens, that works for expanding tracking error tolerance, and a secondary lens designed with the advance technique of non-imaging Kölher freeform arrays, that works for expanding alignment tolerance, it is possible to perform robustly against standard manufacturing errors. In this respect, an innovative photovoltaic optical concentrator design, the DFK, has been already developed (Fig 3). The whole concentration follows a 4-fold scheme in which both, POE and SOE, are divided into 4 identical and symmetric sectors around z axis. [7]. This task is conceived in an iterative scheme so it is expected improvements on the optics designs as the characterization of assembly modules go on. In addition wearing, lifetime and heat handling tests are taking place in order to improve these lenses.

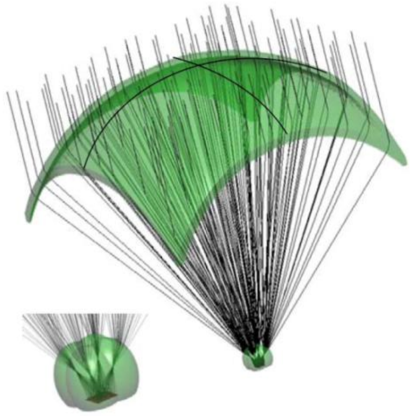

Fig.3. Domed Fresnel-Köhler (DFK) concentrator architecture (POE+SOE). © UPM.

NGCPV project is also working on the development of tools for test and quality control of modules in manufacturing. This concerns in general to the development of methods for unveiling the optical defects of CPV modules during fabrication (MOA: Module Optical Analyzer), as well to obtain the values of significant parameters indoor (like Acceptance Angle), without contribution of the real sun and in a very fast way. In particular the output of this task will provide a system to detect the optical parameters of each module produced by our partners in its factory at Nagoya. The equipment will be an extension of functions for the current solar simulator already installed at the manufacturing line: the key element is the large area mirror to which the MOA will be added.

All these activities reported and improvements that we are proposing and testing are mainly focus on the achievement of a 35% efficiency module when the project finishes (INTREPID Module) [8].

In addition in order to develop a complete system, improved trackers for the INTREPID system need to be developed.

Fig 4. Overview of the 5 arrays installed in Villa Don Fadrique, Toledo (50kW installed). © BSQ Solar.

Finally, this activity has also the mission of contributing to the development of CPV systems by giving feedbacks obtained from a 50kW CPV plant installed with the current market technology. The plant will serve for the work to be performed in previous activity (see section 5) “characterization of 50kW plant” and also to the objective: To evaluate the potential of new materials, device technologies and quantum nanostructures to improve the efficiency of solar cells for CPV, and will serve to the purpose of providing first hand experience in order to work out the power definition for concentration plants and rules for the forecast of their energy production described in WP4. This plant has been commissioned and already finished. It is located in Villa Don Fadrique, Toledo, Spain. (Fig. 4)

7 ACKNOWLEDGEMENTS

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